Comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water of the LNE-LNHB, France and the BIPM in accelerator photon beams

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Abstract
A key comparison has been made between the absorbed dose to water standards of the Laboratoire National Henri Becquerel (LNE-LNHB), France and the BIPM in accelerator photon beams. The results show the standards to be in agreement within the standard uncertainty of the comparison of 5.9 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison has been made between the absorbed dose to water standards of the Laboratoire National Henri Becquerel (LNE-LNHB), France, and the Bureau International des Poids et Mesures (BIPM) in the accelerator photon beam range from 6 MV to 20 MV to update the previous comparison result of 2012 (Picard *et al.* 2013) published in the BIPM key comparison database (KCDB 2020) under the reference BIPM.RI(I)-K6. The comparison took place at the LNE-LNHB accelerator facility in Saclay (France) in February 2020. The comparison was undertaken using two transfer ionization chambers type PTW 30013 of the LNE-LNHB in three radiation beams. The results of the comparison are given in terms of the mean ratio of the calibration coefficients of these transfer instruments determined at the two laboratories for each radiation quality. The final results were supplied by the LNE-LNHB in July 2020.

2. LNE-LNHB irradiation facility

2.1 The LNE-LNHB irradiation facility and reference beam qualities

The comparison was carried out in the LNE-LNHB accelerator facility in Saclay (France), which houses a Varian TrueBeam linear accelerator. This accelerator provides four high-energy photon beams at 6 MV, 10 MV, 15 MV and 20 MV. Due to the limited linac availability, only three beams were selected for the comparison. The radiation qualities are characterized in terms of the tissue-phantom ratio $TPR_{20,10}$, the LNE-LNHB measured values are given in Table 1. All measurements were made with the gantry fixed for horizontal irradiation, with a source-detector distance of 1 m and at the reference depth of 10 g cm^{-2} in water.

Table 1. **LNE-LNHB beam qualities**

Radiation quality	6 MV	10 MV	20 MV
$TPR_{20,10}$	0.665	0.737	0.790

The irradiation area is temperature controlled at 20 °C. Calibrated thermistors measure the temperature of the ambient air and the water. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range from 30 % to 70 %. For the comparison measurements, the beam output was monitored during irradiation using a commercial parallel-plate transmission chamber fixed to a shadow tray, the same transportable arrangement used for previous comparisons in the series BIPM.RI(I)-K6.

3. Details of the standards

3.1 BIPM primary standard

The BIPM primary standard is a graphite calorimeter described by Picard *et al.* (2009). The calorimeter consists of a graphite core placed in a cylindrical graphite jacket; the main characteristics are listed in Table 2.

Table 2. **Characteristics of the BIPM standard**

BIPM standard		Nominal values
Calorimeter core	Diameter / mm	45.0
	Thickness / mm	6.7
Calorimeter jacket	Diameter / mm	60.0
	Thickness / mm	32.0
Standard chamber	Diameter / mm	45.0
	Thickness / mm	11.0
Air cavity	Volume / cm^3	6.8
Wall	Thickness / mm	2.85
Wall material	Graphite of density / g cm^{-3}	1.85
Polarizing voltage	applied to outer electrode / V	+80

The core is equipped with three thermistor pairs connected to three independent d.c. bridges. This core and jacket are placed in an evacuated cubic PMMA vacuum phantom with side length 300 mm. A graphite build-up plate is used to position the calorimeter centre at the reference depth of 10 g cm^{-2}. Two nominally-identical parallel-plate ionization chamber standards with graphite walls and collector, similar in design to the existing BIPM standards for air kerma and absorbed dose to water, were fabricated to serve in the determination of the absorbed dose to water from the measured absorbed dose to the graphite core. The first chamber is housed in a graphite jacket, nominally identical to the calorimeter jacket, and is positioned in the same PMMA vacuum phantom but at ambient air pressure, replacing the calorimeter core and its jacket. The second chamber is housed in a waterproof polyethylene sleeve and mounted at a depth of 10 g cm^{-2} in a PMMA water phantom with the same outer dimensions and PMMA window thickness (4 mm) as the vacuum phantom.

3.2 LNE-LNHB Primary standard

The LNE-LNHB primary standard is a graphite calorimeter (GR9), used to measure the mean absorbed dose to the graphite of its core, D_{core}, in accelerator beams (Delaunay *et al.* 2014). The absorbed dose to water D_{w} is determined from the absorbed dose to graphite D_{core} and Monte Carlo calculations (EGSnrc and PENELOPE codes) to convert from graphite to water.

4. Determination of the absorbed dose to water

4.1 Absorbed dose to water at the BIPM: formalism and method

The BIPM determination of absorbed dose to water is based on calorimetric and ionometric measurements combined with Monte Carlo calculations. The method is described in a number of previous comparison reports, for example Kessler *et al.* (2019). The absorbed dose to water at the reference depth, $D_{\text{w,BIPM}}$, is evaluated as:

$$D_{\text{w,BIPM}} = D_{\text{c}} \frac{Q_{\text{w,st}}}{Q_{\text{c,st}}} \left(\frac{D_{\text{w}}}{D_{\text{c}}}\right)^{\text{MC}} \left(\frac{D_{\text{cav,c}}}{D_{\text{cav,w}}}\right)^{\text{MC}} k_{\text{rn}} \tag{1}$$

where

D_{c}	measured absorbed dose to the graphite core;
$Q_{\text{c,st}}$	ionization charge measured by the standard chamber positioned in the graphite jacket, replacing the core;
$Q_{\text{w,st}}$	ionization charge measured by the standard chamber positioned in water;
$(D_{\text{w}}/D_{c})^{\text{MC}}$	calculated ratio of absorbed dose to water and to the graphite core using Monte Carlo simulations;
$(D_{\text{cav,c}}/D_{\text{cav,w}})^{\text{MC}}$	calculated ratio of cavity doses in graphite and in water using Monte Carlo simulations;
k_{rn}	measured correction for radial non-uniformity in water.

The ionization charges $Q_{\text{w,st}}$ and $Q_{\text{c,st}}$ are normalized to 293.15 K and 101.325 kPa and corrected for ion recombination. In practice, two nominally-identical standard chambers are used; the air cavity volume for each is known and a correction k_{vol} is made for the small difference in volume with a relative standard uncertainty of 3 parts in 10^4.

Equation 1 can also be expressed as

$$\begin{aligned} D_{\text{w,BIPM}} &= Q_{\text{w,st}} \frac{D_{\text{c}}}{Q_{\text{c,st}}} C_{\text{w,c}} k_{\text{rn}} \\ &= Q_{\text{w,st}} N_{D,\text{c,st}} C_{\text{w,c}} k_{\text{rn}} \end{aligned} \tag{2}$$

where

$C_{\text{w,c}}$ represents the total Monte Carlo conversion factor;

$N_{D,\text{c,st}}$ is the measured calibration coefficient for the standard chamber in graphite.

The conversion factor $C_{\text{w,c}}$ and the calibration coefficients $N_{D,\text{c,st}}$ for the standard chamber in graphite for given $\text{TPR}_{20,10}$ values are taken to be those derived from quadratic fits, as explained in Kessler *et al.* (2019). Figure 1 shows the conversion factors plotted as a function of the calculated $TPR_{20,10}$. Figure 2 shows the normalized $N_{D,c,st}$ determinations and a quadratic fit to the data; the plot also shows the coefficients determined at the DOSEO facility in Saclay (France) using an Elekta linear accelerator, which has been characterized for use as a BIPM reference facility. These data are included in the fit.

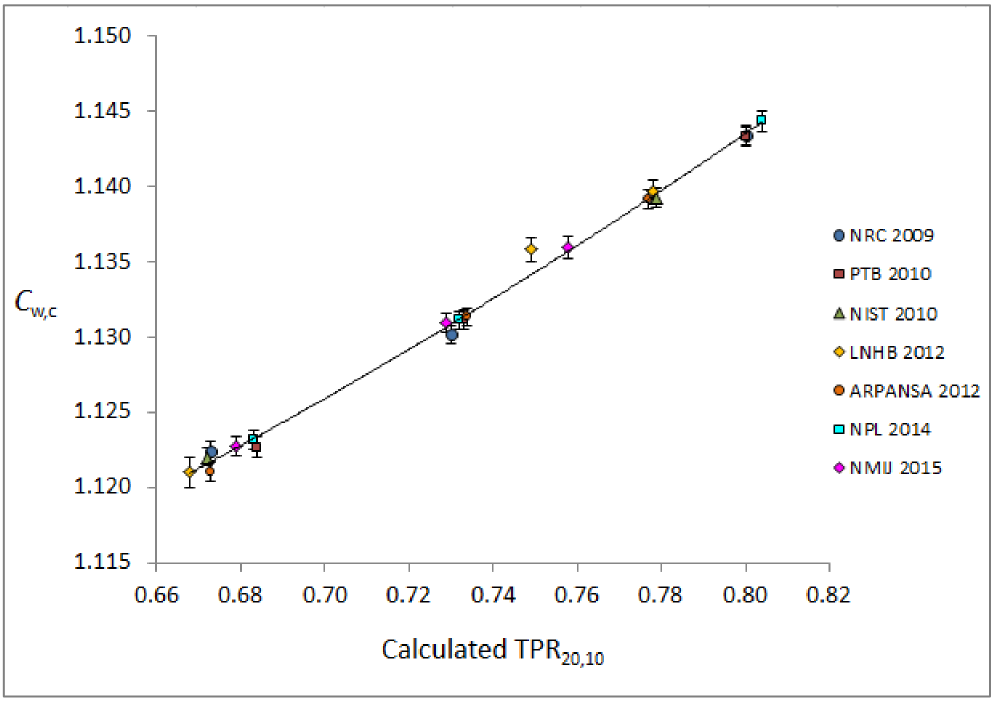

Figure 1. The dose conversion factor $C_{w,c}$ for the BIPM standard, calculated using the phase-space files supplied by participating NMIs. The line is a weighted quadratic fit to the data; the deviations about this line are consistent with the typical statistical standard uncertainty of 5 parts in 10^4.

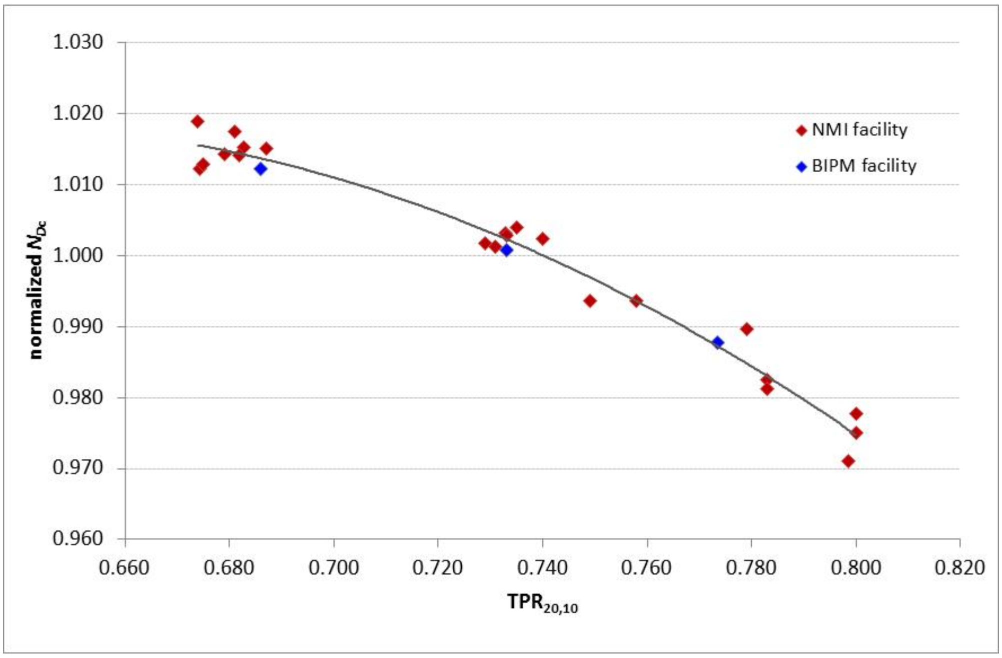

Figure 2. The calibration coefficients $N_{D,c,st}$ determined by the BIPM at various NMI facilities (red) and at the BIPM facility (blue), normalized to the mean, as a function of the measured $TPR_{20,10}$. The solid line is a quadratic fit to the combined data set.

4.2 Absorbed dose to water at the BIPM: practical determination

Since 2017, the BIPM has been calibrating periodically a set of 4 reference chambers: types NE 2571 (1 chamber), PTW 30012 (2 chambers) and PTW 30013 (one chamber), principally at the BIPM facility at DOSEO. The chambers have also been calibrated at the Technical University of Denmark DTU and at the LNE-LNHB; these calibrations involve accelerators supplied by two different manufacturers. For the present comparison at the LNE-LNHB accelerator facility, instead of using the primary standard, the NE 2571 chamber was used as the BIPM reference.

The absorbed dose to water was thus determined as

$$D_{\mathrm{w,BIPM}} = Q_{\mathrm{w,ref\,ch}} N_{D,\mathrm{w,ref\,ch}} k_{\mathrm{rn}} k_{\mathrm{s}} \tag{3}$$

where

$Q_{\mathrm{w,ref\,ch}}$	ionization charge measured by the reference chamber positioned in water (normalized to the monitor chamber)
$N_{D,\mathrm{w,ref\,ch}}$	calibration coefficient of the reference chamber
k_{rn}	radial non-uniformity correction factor for the reference chamber
k_s	ion recombination correction factor

The ionization charge $Q_{\mathrm{w,ref\,ch}}$ is normalized to 293.15 K and 101.325 kPa; no correction for humidity is applied.

The correction factor k_{s} for losses due to ion recombination for the reference standard was determined using the method of Niatel as described by Boutillon (1998) for continuous radiation and implemented for pulsed radiation by Picard *et al.* (2011). The recombination correction k_{s} for pulsed radiation can be expressed as:

$$k_{\mathrm{s}} = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} Q_{\mathrm{p}} \tag{4}$$

where Q_{p} is the charge per pulse expressed in pC, k_{init} is the initial recombination and diffusion and k_{vol} is the volume recombination coefficient. Table 3 gives the values for k_{init} and k_{vol}, for the operating voltage of 250 V. For a typical charge per pulse of up to 10 pC, k_{s} is of the order of 1 part in 10^2 and the standard uncertainty for k_{s} is estimated to be 3 parts in 10^4, as shown in Table 9. The correction factors for the three radiation qualities are presented in Table 4.

Table 3. Ion recombination for the BIPM reference chamber NE 2571

Coefficient	Value
initial recombination and diffusion, k_{init}	12.9×10^{-4}
volume recombination coefficient, k_{vol} / pC^{-1}	7.1×10^{-4}

The factors that correct for the non-uniformity of the beams were calculated from the beam profiles in water measured by the LNE-LNHB. For thimble chamber types, the correction factors for the three different beams are less than 1 part in 10^3 with an estimated relative standard uncertainty of 3 parts in 10^4, as shown in Table 9. The values are presented in Table 4.

Table 4. Correction factors for the BIPM reference chamber NE 2571

Radiation quality	6 MV	10 MV	20 MV
ion recombination k_s	1.0053	1.0056	1.0107
radial non-uniformity k_{rn}	0.9997	0.9993	1.0009

4.3 Absorbed dose to water at the LNE-LNHB

As explained in section 3.2, the LNE-LNHB determination of absorbed dose to water is based on calorimetric measurements in the GE Saturn 43 linac combined with Monte Carlo calculations. The absorbed dose to water at the reference depth, D_w, is evaluated as:

$$D_\mathrm{w} = D_\mathrm{core} \left[\frac{D_\mathrm{w}(\mathrm{V})}{D_\mathrm{core}}\right]_\mathrm{MC} k_i \, k_\mathrm{prof}(\mathrm{V}) \quad (5)$$

where

D_{core}	measured absorbed dose to graphite
$[D_{core}]_{MC}$	absorbed dose to graphite calculated using MC codes
$[D_w(V)]_{MC}$	absorbed dose to water in a volume V calculated using MC codes
k_i	correction factor for the non-graphite material in the core
$k_{prof}(V)$	correction factor for the difference between calculating $[D_w(V)]_{MC}$ for a volume V rather than for the reference point

A reference chamber NE 2571 was calibrated against the graphite calorimeter GR9 in the GE Saturn 43 linac. Using this reference chamber, a set of transfer chambers, including the PTW 30013 used for the comparison, were cross-calibrated in these accelerator beams.

For the reference chamber as well as for the transfer chambers, the following expression was used to fit the measured calibration coefficients as a function of the Saturn 43 $TPR_{20,10}$ to obtain the parameters a, b and c:

$$\ln(N_{D,\mathrm{w}}) = a + b\,\mathrm{TPR}_{20,10} \ln(\mathrm{TPR}_{20,10}) + c / \ln(\mathrm{TPR}_{20,10}) \quad (6)$$

The beam quality index $TPR_{20,10}$ is corrected for the difference in saturation between 10 cm and 20 cm depth but not corrected either for the differences in polarity effect or for the radial non-uniformity of the beam at the two depths.

All the ionization currents were normalized to the reference conditions T_0 = 293.15 K, p_0 = 101.325 kPa and humid air (50 %) and corrected for ion recombination k_s and the radial non-uniformity of the beam k_{rn}.

5. Comparison procedure

The comparison of the LNE-LNHB and BIPM standards was carried out indirectly in the LNE-LNHB accelerator beams using the calibration coefficients $N_{D,\mathrm{w,lab}}$ for two transfer chambers given by

$$N_{D,\mathrm{w,lab}} = \dot{D}_\mathrm{w,lab} / I_\mathrm{lab} \quad (7)$$

where $\dot{D}_\mathrm{w,\,lab}$ is the water absorbed dose rate determined by a given laboratory, the LNE-LNHB or the BIPM, and I_{lab} is the corresponding ionization current for a transfer chamber measured by each laboratory, using its own measurement system, in the LNE-LNHB beams.

The ionization chambers PTW 30013, serial number 8859 and 8861, belonging to the LNE-LNHB, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 5.

Table 5. Characteristics of the transfer chamber PTW 30013

Parameter	PTW 30013
External diameter / mm	6.85
Nominal volume / cm^3	0.6
Wall material	0.335 mm PMMA + 0.09 mm graphite
Wall thickness	0.0565 g cm^{-2}
Polarizing voltage / V	+300[a]

[a] Potential applied to the outer electrode

The essential details for the determination of the calibration coefficients $N_{D,\mathrm{w}}$ for the transfer chambers are described below.

Positioning

The chambers were positioned by each laboratory with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source.

Applied voltage and polarity

A collecting voltage of 300 V (positive polarity) was applied to the outer electrode of the PTW chambers at least 30 min before any measurements were made. No corrections were applied by either laboratory for polarity.

Ion recombination

Ion recombination was measured by the BIPM for each chamber using the two-voltage technique, as described in the IAEA protocol TRS 398 (IAEA 2000). The results are presented in Table 6. For the LNE-LNHB, the correction for ion recombination was determined in the same way. The results are also included in the table. The LNE-LNHB results for ion recombination are in agreement with the BIPM values within the uncertainties stated in Tables 10 and 12.

Radial non-uniformity correction

The correction factors calculated by the BIPM for the radial non-uniformity of the beam over the section of the transfer chambers were calculated from the beam profiles in water measured by the LNE-LNHB; they are the same as those for the BIPM reference chamber NE 2571 given in Table 4, with an uncertainty of 3 parts in 10^4. The correction factors applied by the BIPM and the LNE-LNHB are summarized in Table 6. The LNE-LNHB results for radial non-uniformity are in agreement with the BIPM values within the uncertainties.

Table 6. Correction factors for the transfer chambers PTW 30013

Radiation quality			6 MV	10 MV	20 MV
ion recombination k_s	BIPM	PTW 8859	1.0040	1.0037	1.0073
		PTW 8861	1.0039	1.0040	1.0076
	LNE-LNHB		1.0034	1.0035	1.0071
radial non-uniformity k_{rn}	BIPM		0.9997	0.9993	1.0009
	LNE-LNHB		0.9998	0.9994	1.0004

Charge measurements

The charge was measured by the BIPM using a Keithley electrometer, model 6517, and a set of calibrated external capacitors. The same kind of instruments are used by LNE-LNHB. The capacitors are in sealed boxes filled with dried air. The chambers were pre-irradiated for at least 10 min (≈ 20 Gy) by the BIPM and the LNE-LNHB before any measurements were made.

Ambient conditions

For the BIPM and LNE-LNHB arrangements, the water temperature is measured for each current measurement and it was stable to better than 0.1 °C.

The ionization current is normalized to 293.15 K and 101.325 kPa for both laboratories. Relative humidity is in the range from 30 % to 70 % at the LNE-LNHB facility. No correction for humidity is applied to the ionization current measured by either laboratory.

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and the thickness of the PMMA front window of the water phantom (4 mm for the BIPM and 4.01 mm for the LNE-LNHB) is included as a water-equivalent thickness in g cm^{-2} when positioning the chamber.

As the transfer instruments are waterproof chambers, no sleeve was used for the present comparison.

6. Results of the comparison

6.1 Measurement results

Each transfer chamber was set-up and measured by the BIPM on two separate occasions. The results were reproducible to better than 1 part in 10^3. For the LNE-LNHB measurements, the chambers were calibrated on two separate occasions as well. The results were reproducible to better than 1 part in 10^3.

As mentioned in section 4.3, the transfer chambers were cross-calibrated in the Saturn 43 linear accelerator and the results were fitted with the expression (6). The calibration coefficients used for the present comparison made in the Varian TrueBeam accelerator beams were obtained by interpolation using the same expression. As an additional verification, the transfer chambers were also cross-calibrated in terms of absorbed dose to water in the Varian TrueBeam. For these measurements, the NE 2571 calibration coefficients $N_{D\mathrm{w}}$ for the Varian TrueBeam $\mathrm{TPR}_{20,10}$ were obtained using the expression (6). The calibration coefficients for the transfer chambers obtained by these two different routes agree at the level of 1 part in 10^3, well within the relative standard uncertainty, as presented in 6.2. The uncertainties introduced due to the cross-calibration process and the use of the fitting formula (6) in the determination of the calibration coefficients are considered in the current ratio $Q_{\mathrm{w,reference\ ch}}$ / $Q_{\mathrm{w,transfer\ ch}}$ and included in Table 12.

To check the stability of the chambers, cross-calibrations of three ionization chambers were made before and after the BIPM measurements. These results give rise to the relative standard uncertainty of 1 part in 10^4 to represent the transfer chambers stability.

The result of the comparison, $R_{D,\mathrm{w}}$, is expressed in the form

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,LNE\text{-}LNHB}} / N_{D,\mathrm{w,BIPM}} \qquad (8)$$

The results for each chamber are presented in Table 7.

Table 7. Calibration coefficients for the transfer chambers

Radiation quality	6 MV	10 MV	20 MV
PTW 30013-8859			
$N_{D,\mathrm{w,LNE\text{-}LNHB}}$ / Gy µC^{-1}	52.76	52.19	51.12
$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	52.87	52.37	51.40
PTW 30013-8861			
$N_{D,\mathrm{w,LNE\text{-}LNHB}}$ / Gy µC^{-1}	52.66	52.07	51.10
$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	52.80	52.28	51.27

The final results $R_{D,\mathrm{w,LNE\text{-}LNHB}}$ in Table 8 are evaluated as the mean for the two transfer chambers. For each quality, the corresponding uncertainty s_{tr} is the standard uncertainty of this mean, derived from the difference in the two results. The mean value of s_{tr} for the three qualities, $s_{\mathrm{tr,comp}}$ = 0.0005, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 13.

The results shown in Table 8 demonstrate the agreement between the two standards for absorbed dose to water at the level of 4 parts in 10^3 which is within the relative standard uncertainty of the comparison of 5.9 parts in 10^3 evaluated below.

Table 8. Comparison results

Radiation quality	6 MV	10 MV	20 MV
$N_{D,\mathrm{w,LNE\text{-}LNHB}}/N_{D,\mathrm{w,BIPM}}$ using # 8859	0.9980	0.9965	0.9946
$N_{D,\mathrm{w,LNE\text{-}LNHB}}/N_{D,\mathrm{w,BIPM}}$ using # 8861	0.9974	0.9959	0.9966
s_{tr}	0.0002	0.0003	0.0010
$R_{D,\mathrm{w,LNE\text{-}LNHB}}$	0.9977	0.9962	0.9956

6.2 Uncertainties

The uncertainties associated with the BIPM primary standard and the calibration of the BIPM reference chamber are listed in Table 9. Table 10 summarizes the uncertainties associated with the calibration of the LNE-LNHB transfer chambers used for the comparison.

Table 9. Uncertainties associated with the BIPM standard and the calibration of the BIPM reference chamber

Relative standard uncertainty (1)	$10^2 \times u_{i\mathrm{A}}$	$10^2 \times u_{i\mathrm{B}}$
$N_{D,\mathrm{c}}$	0.23	0.14
$C_{\mathrm{w,c}}$	0.05	0.25
$Q_{\mathrm{w,st}}/Q_{\mathrm{w,BIPM\ ref\ ch}}$	0.05	0.05
$k_{\mathrm{rn,st}}$	–	0.10
$k_{\mathrm{s,st}}$	–	0.05
$k_{\mathrm{vol,st}}$	–	0.03
Depth standard	–	0.05
$k_{\mathrm{rn,BIPM\ ref\ ch}}$ (2)	–	0.03
$k_{\mathrm{s,BIPM\ ref\ ch}}$ (2)	–	0.03
Depth BIPM reference chamber	–	0.05
Stability $Q_{\mathrm{w,st}}/Q_{\mathrm{w,BIPM\ ref\ ch}}$	0.06	–
$N_{D,\mathrm{w,BIPM\ ref\ ch}}$	0.25	0.32

(1) expressed as one standard deviation.
u_{iA} represents the relative uncertainty estimated by statistical methods, type A
u_{iB} represents the relative uncertainty estimated by other methods, type B.
(2) uncertainty removed from the analysis when the reference chamber is used to calibrate the transfer chamber (Table 10).

Table 10. Uncertainties associated with the calibration of the LNE-LNHB transfer chambers

Relative standard uncertainty	$10^2 \times u_{i\mathrm{A}}$	$10^2 \times u_{i\mathrm{B}}$
$N_{D,\mathrm{w,BIPM\ ref\ ch}}$	0.25	0.32
$Q_{\mathrm{w,BIPM\ ref\ ch}}/Q_{\mathrm{w,tr\ ch}}$	0.05	0.05
Depth BIPM reference chamber	–	0.05
Depth transfer chamber	–	0.05
$k_{\mathrm{s,tr\ ch}}$	–	0.03
short-term reproducibility	0.05	–
$N_{D,\mathrm{w,tr\ ch}}$	0.26	0.33

For the LNE-LNHB, the uncertainties are listed in Table 11 and Table 12 for the standard and the calibration of the chambers used for the comparison, respectively. The combined standard uncertainty u_{c} for the comparison results $R_{D,\mathrm{w,LNE\text{-}LNHB}}$ is presented in Table 13.

Table 11. Uncertainties associated with the LNE-LNHB standard

Relative standard uncertainty	$10^2 \times u_{i\mathrm{A}}$	$10^2 \times u_{i\mathrm{B}}$
$D_{\mathrm{core/mu}}/Q_{\mathrm{w,ref/mu}}$	0.04	0.15
$k_{\mathrm{pol,ref}}$	0.03	0.02
$k_{\mathrm{s,ref}}$	0.05	0.02
$k_{\mathrm{rn,ref}}$	0.08	0.02
$[D_{\mathrm{w,V}}/D_{\mathrm{core}}]_{\mathrm{MC}}$	0.12	0.20
k_{i}	–	0.10
$k_{\mathrm{prof,V}}$	0.08	0.04
$N_{D\mathrm{w,ref}}$	0.18	0.27

Table 12. Uncertainties associated with the calibration of the transfer chambers at the LNE-LNHB (3 cross-calibrations)

Relative standard uncertainty	$10^2 \times u_{i\mathrm{A}}$	$10^2 \times u_{i\mathrm{B}}$
$N_{D\mathrm{w,ref}}$	0.18	0.27
$Q_{\mathrm{w,tr\ ch\ /\ mu}}/Q_{\mathrm{w,ref\ /\ mu}}$	-	0.19
$k_{\mathrm{s,tr\ ch}}/k_{\mathrm{s,ref}}$	-	0.14
$N_{D,\mathrm{w,tr\ ch}}$	0.18	0.36

Table 13. Uncertainties associated with the comparison result

Relative standard uncertainty	$10^2 \times u_{i\mathrm{A}}$	$10^2 \times u_{i\mathrm{B}}$
$N_{D,\mathrm{w,LNE\text{-}LNHB}}/N_{D,\mathrm{w,BIPM}}$	0.31	0.49
$k_{\mathrm{rn,tr\ ch}}$	–	0.03
Transfer chambers $s_{\mathrm{tr,comp}}$	0.05	–
$R_{D,\mathrm{w,LNE\text{-}LNHB}}$	0.59	

6. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here $D_{\mathrm{w,BIPM}}$, is taken as the key comparison reference value (KCRV) (Allisy-Roberts *et al.* 2009). It follows that for each NMI *i* having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (D_{\mathrm{w}i} - D_{\mathrm{w,BIPM}i})/ D_{\mathrm{w,BIPM}i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 14 gives the values for D_i and U_i for each NMI, *i,* taken from the BIPM key comparison database (KCDB 2020) and this report. These data are presented graphically in Figure 3.

Table 14. Degrees of equivalence

Beam quality corresponding to measured $TPR_{20,10}$ between 0.63 (included) and 0.71 (excluded)

	D_i	U_i
Lab *i*	/ (mGy/Gy)	
NRC	-2.7	11.0
PTB	1.3	10.4
NIST	3.5	11.4
ARPANSA	-3.5	11.0
NPL	-2.7	12.4
VSL	-4.1	10.8
NMIJ	-3.4	9.4
NIM	-8.3	12.0
KRISS	7.8	12.0
METAS	-1.7	13.2
LNE-LNHB	-2.3	11.8

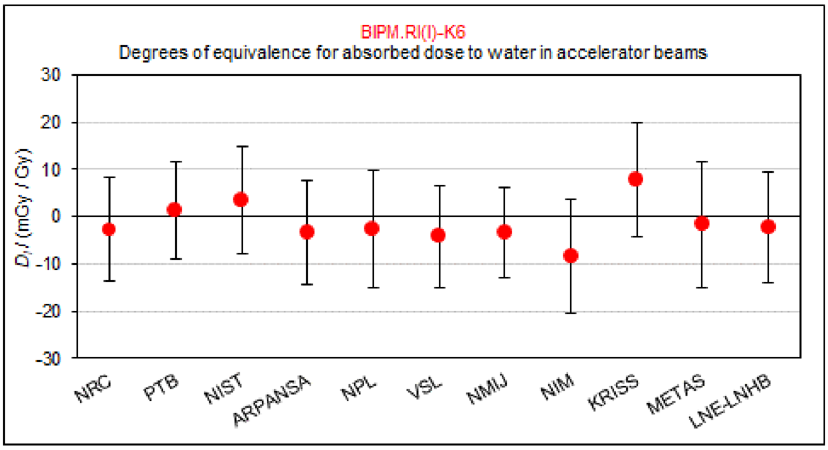

Figure 3. Graph of the degrees of equivalence with the KCRV

Beam quality corresponding to measured $TPR_{20,10}$ between 0.71 (included) and 0.77 (excluded)

	D_i	U_i
Lab *i*	/ (mGy/Gy)	
NRC	0.8	11.0
PTB	3.4	11.4
ARPANSA	-7.6	12.0
NPL	-0.5	13.2
VSL	-4.2	12.8
NMIJ	-4.1	11.0
NIM	-5.9	11.8
KRISS	5.6	12.0
METAS	-3.2	13.2
LNE-LNHB	-3.8	11.8

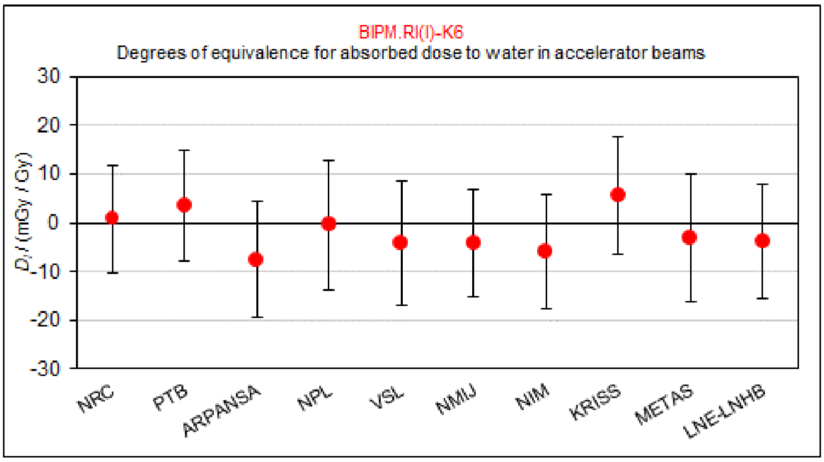

Figure 3. Graph of the degrees of equivalence with the KCRV

Beam quality corresponding to measured $TPR_{20,10}$ between 0.77 (included) and 0.81(included)

	D_i	U_i
Lab *i*	/ (mGy/Gy)	
NRC	-5.8	11.0
PTB	1.8	12.8
NIST	-4.2	11.8
ARPANSA	-6.8	11.8
NPL	-4.3	16.2
VSL	-0.9	15.0
KRISS	8.5	12.0
METAS	-1.2	13.2
LNE-LNHB	-4.4	11.8

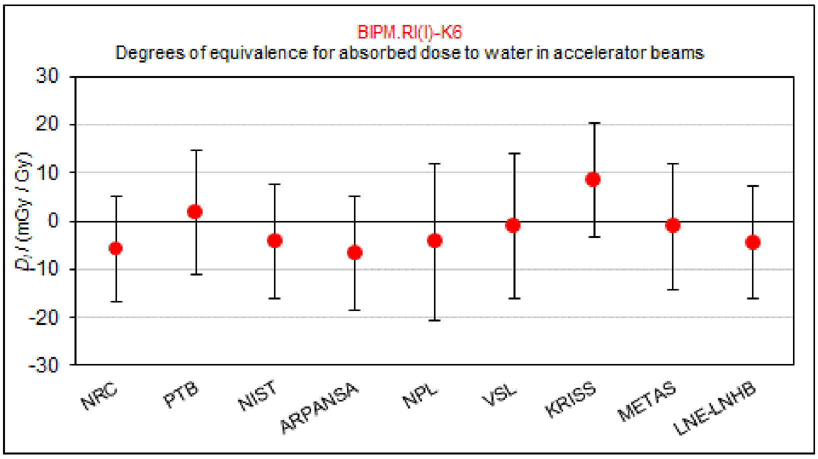

Figure 3. Graph of the degrees of equivalence with the KCRV

7. Conclusions

A new key comparison has been carried out between the LNE-LNHB and the BIPM standards for absorbed dose to water in accelerator photon beams, using two ionization chambers as transfer instruments. The comparison result is evaluated as the ratio of the calibration coefficients measured by the LNE-LNHB and the BIPM. The results show the standards to be in agreement within the standard uncertainty of the comparison of 5.9 parts in 10^3. The present results are in agreement within the uncertainties with the results of the previous comparison (0.995 at 6 MV and 12 MV; 0.994 at 20 MV, with a combined standard uncertainty of 5 parts in 10^3) carried out in the GE Saturn 43 accelerator beams in 2012.

When compared with the results for the other laboratories that have carried out comparisons in terms of absorbed dose to water, the LNE-LNHB standard for absorbed dose to water is in good agreement with the ensemble of results.

Note that the data presented in the tables, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database (KCDB 2020).

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